LEVEL II

AD A056711

AFGL-TR-78-0003

DEVELOPMENT, TEST, AND CALIBRATION OF A THREE-AXIS ACCELEROMETER SYSTEM

William G. Lange

Bell Aerospace Textron
P.O. Box One
Buffalo, New York 14240

Final Report
6 December 1973 through 31 December 1977

15 December 1977

Approved for public release; distribution unlimited

This research was supported by the Air Force In-House Laboratory Independent Research Fund

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

78 07 24 021

Qualified requestors may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

18 19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-78-0003	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Development, Test, and Calibration of a Three-Axis Accelerometer System.		5. TYPE OF REPORT & PERIOD COVERED Final - 6 Dec. 1973 to 31 December 1977
		6. PERFORMING ORG. REPORT NUMBER 14 6384-928032
7. AUTHOR(s) 10 William G. Lange		8. CONTRACT OR GRANT NUMBER(s) 15 F19628-74-C-0114
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bell Aerospace TEXTRON P. O. Box One Buffalo, New York 14240		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61101F 16 ILIR 4C01 17 4C
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Contract Monitor: Frank A. Marcos/LKB		12. REPORT DATE 11 15 Dec[redacted]77
		13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 33p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

9 Final rept. 6 Dec 73-31 Dec 77,

18. SUPPLEMENTARY NOTES

This research was supported by the Air Force In-House Laboratory Independent Research Fund

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Accelerometer
Acceleration
Electrostatic Accelerometer
Atmospheric Density Measurement

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development test and calibration of a single proof mass three axis electrostatic accelerometer intended for atmospheric density measurements in an earth orbiting satellite.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

408 855

TABLE OF CONTENTS

1. INTRODUCTION

This report describes the design, fabrication, and test of a single proof mass three axes electrostatic accelerometer intended for measurement of upper atmospheric density in an earth orbiting satellite.

The accelerometer design is based on the flight proven single axis version MESA, which has been modified by instrumenting both cross axes with precision constrainment loops.

2. INSTRUMENT DESIGN

The mechanical assembly of the three axes MESA is a combination of parts designed for easy machining and assembly plus providing the proper mechanical and electrical properties essential to performance.

Figure 2-1 is an exploded view of the instrument. It is composed of seven basic parts, two of which are identical pairs.

In the center of the assembly is the "proof mass" in the form of a flanged cylinder. The proof mass is constrained in all three axes by means of electrostatic forces generated by electrodes. There are a total of 14 electrodes, three on each of the "forcer" rings facing both sides of the flange and eight on the "carrier" cylinder facing the inside of the proof mass cylinder. The electrodes serve to detect motion of the proof mass by means of an a-c capacitive pickoff bridge and forcing by means of a direct coupled d-c voltage. The proof mass is thus constrained

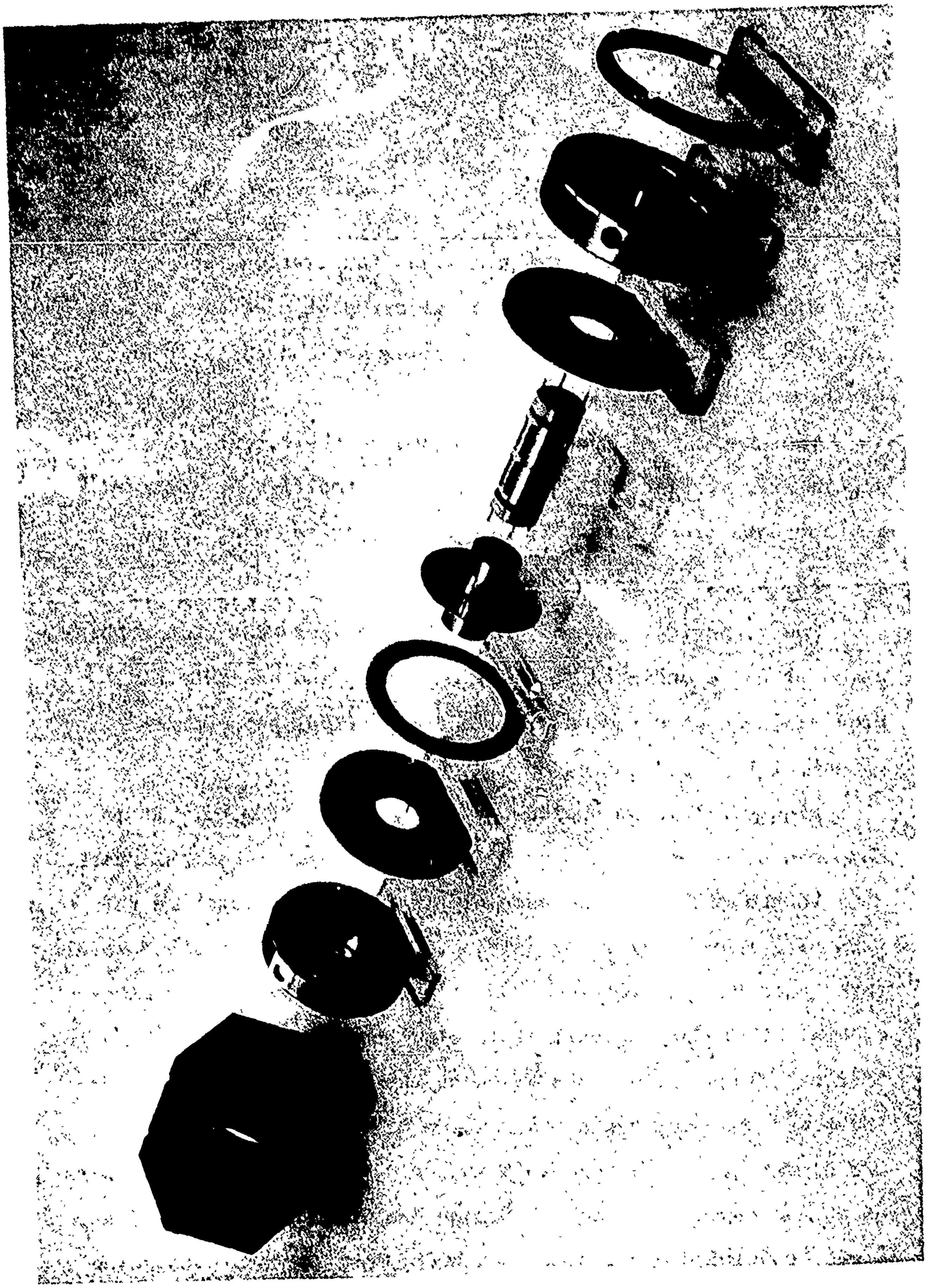


FIGURE 2-1

by a force rebalance loop, the output of which is a signal directly proportional to input acceleration. Details of constrainment loop operation are described in the electrical design section of this report.

The Z axis is along the axial centerline of the proof mass cylinder. The X and Y axes are perpendicular to the cylinder and defined by the four pairs of electrodes on the carrier.

The spacing between any electrode and the proof mass when constrained or centered is a nominal .0025 inches. The forcer and carrier are held in position by a combination of the instrument case and two "retainers". These retainers center the assembly within the case and are in turn held in place by a large ring nut at one end. The opposite end seats against a flange on the inside of the case.

Extensive research and experience has led to the various materials used. The proof mass is beryllium, the carrier and forcers are ceramic with vacuum deposited electrodes, the retainers are titanium, the nut is beryllium copper, and the case and covers are aluminum.

The forcer, carrier, spacer, and proof mass materials have matching coefficients of expansion to minimize scale factor temperature coefficients. The retainer, nut, and housing have the necessary strength to keep the active inner elements aligned, provide a mechanical interface, and hermetically sealed enclosure.

The materials have been selected for machinability and require no protective finish to prevent corrosion or scoring during assembly and disassembly. The only finish is a chemical alodine film on the aluminum case.

The unit is completely sealed by means of an epoxy which has been especially formulated for metal bonding. The cover and terminal bond cross sections are designed for maximum length leak path and strength.

Upon sealing, the assembly is filled with dry nitrogen and a small amount of helium for leak detection.

The small gap between proof mass and electrodes in combination with the dry gas, provides a high degree of damping. This allows the unit to survive launch vibration environments without power application.

3. ELECTRONIC DESIGN

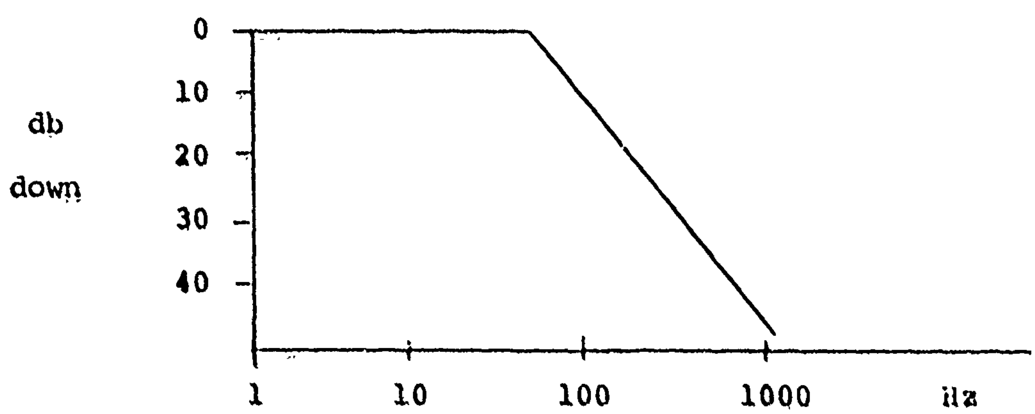
Measurement of acceleration is accomplished by sensing motion of the proof mass with respect to the instrument case. An electrostatic force is then generated to oppose this motion in a direction to restore the proof mass to its null or zero input position.

The restoring force is generated by a d-c voltage proportional to input acceleration. This voltage is also converted to a digital output signal.

Figures 3-1 and 3-2 are block diagrams of the constrainment loop connection to the electrodes within the mechanical assembly.

The X and Y axes are identical, each using two constrainment circuits to prevent rotation about the proof mass center of gravity. The Z axis requires only a single circuit. Figure 3-3 is a block diagram of the individual circuits within the constrainment loop. The bridge preamplifier is attached directly to the instrument case. The remaining circuits are made up of discrete components mounted on plug-in printed circuit boards.

The position pickoff sensing uses a capacitive bridge circuit with a 100 kHz excitation signal. The pickoff circuit response is bandwidth limited on the high end by proof mass damping, and has a typical response curve as shown in Figure 3-4.



Pickoff Sensing Frequency Response

Figure 3-4

FORCE REBALANCE LOOP, X AND Y AXES
(Y ONLY SHOWN)

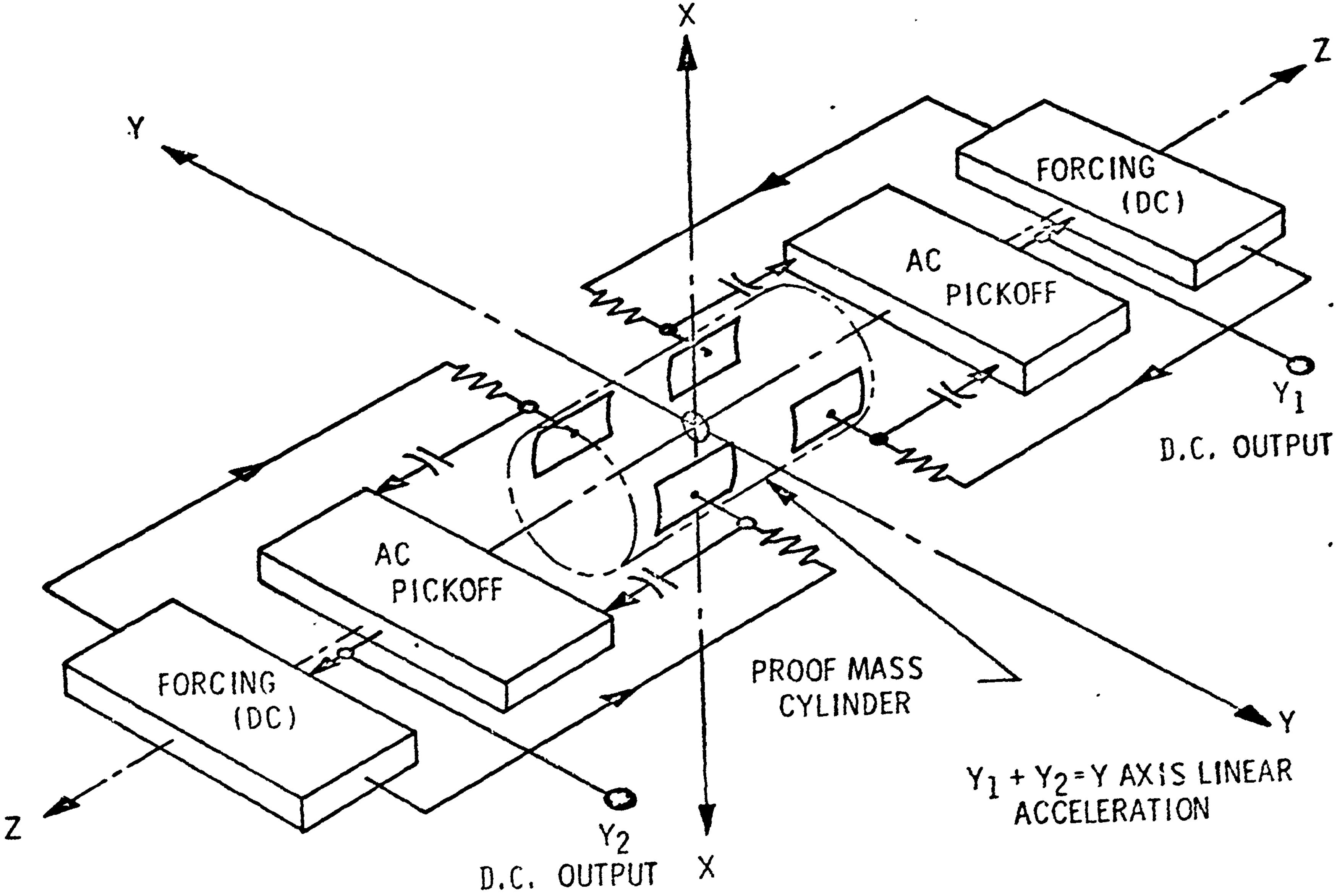


FIGURE 3-1

FORCE REBALANCE LOOP, Z AXIS

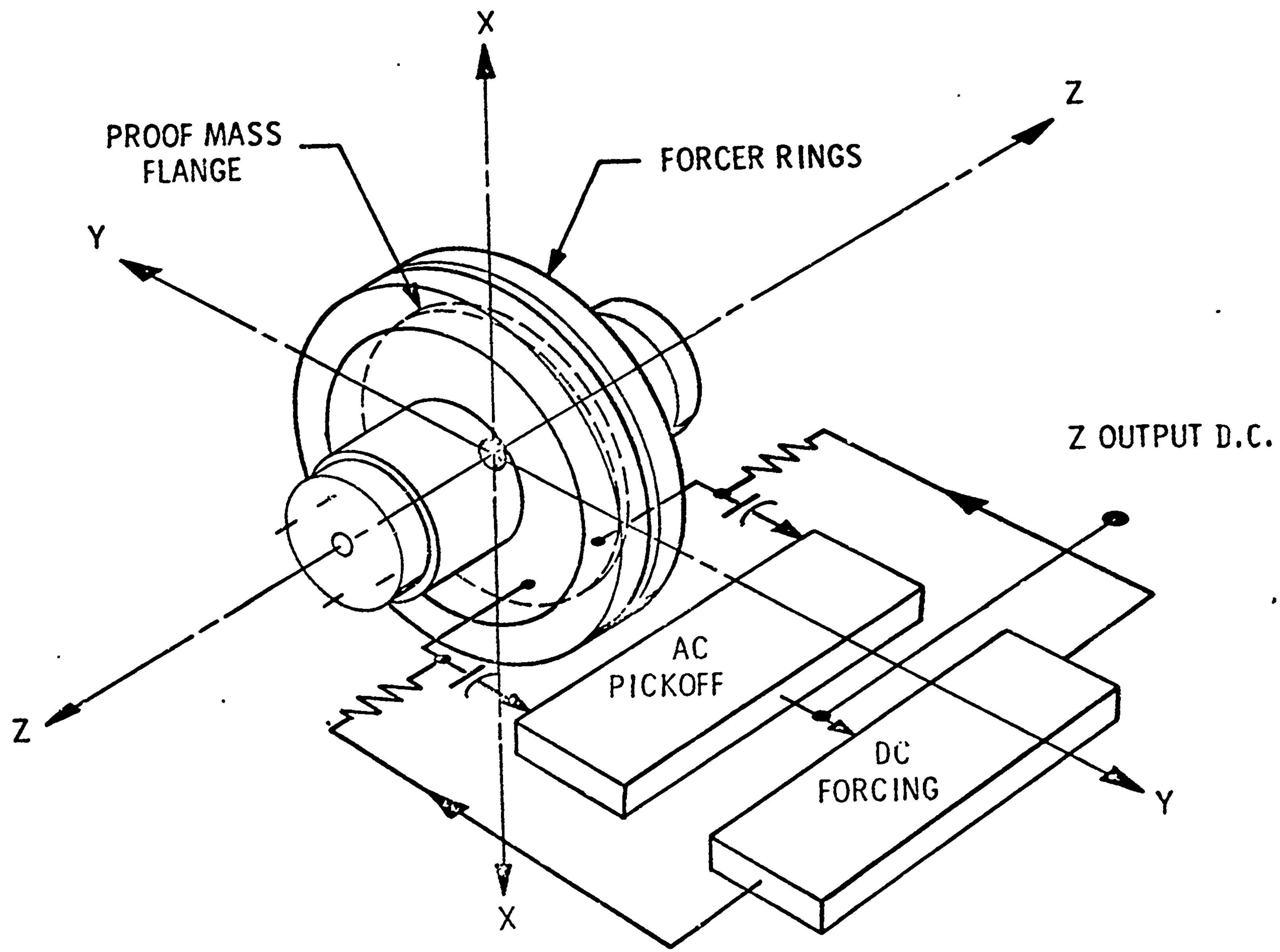
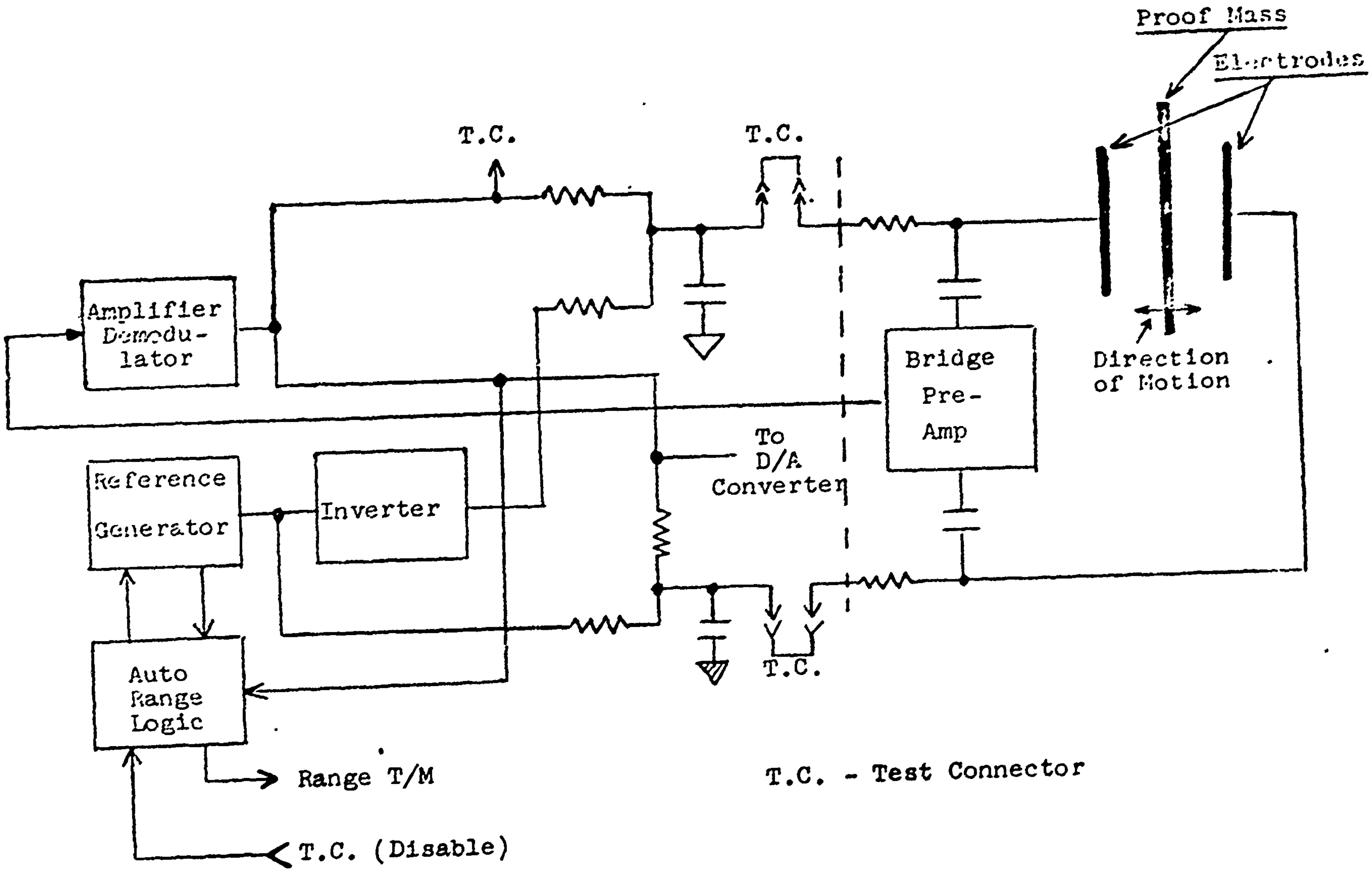


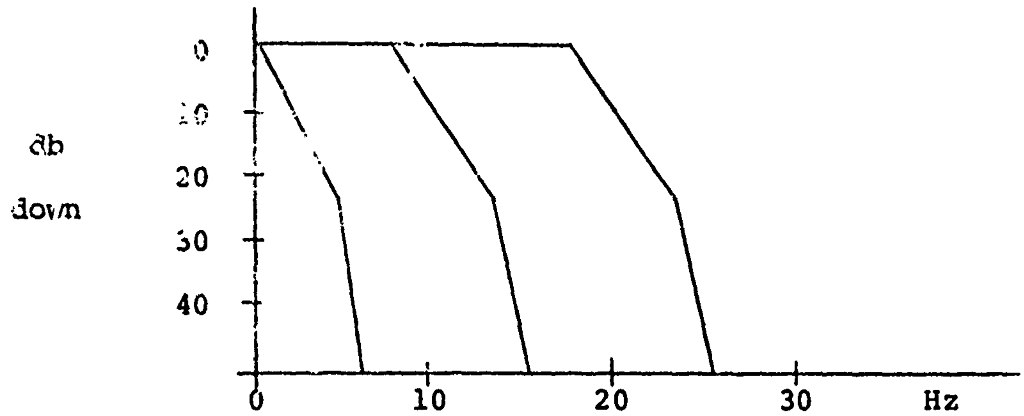
FIGURE 3-2



BLOCK DIAGRAM - CONSTRAINMENT ELECTRONICS

FIGURE 3-3

The forcing section of the constrainment loop uses d-c and is bandwidth limited by a combination of amplifier feedback, summing network, and output RC network. The overall response and rolloff rate is optimized for this application. The response is limited to the lowest value which will not cause data attenuation. This results in high immunity to acceleration noise from other sources on the satellite. Typical response curves for this application are shown in Figure 3-5 and may be different for each axis if required.



Typical Forcing Frequency Response

Figure 3-5

The auto range logic accepts two input signals and generates two output signals. One input is a 2-bit word from the reference generator to indicate which range is in use. The second input is the d-c output of the constrainment loop indicating the input level with respect to full scale. When the input falls outside of the set switch level limits, the output of the reference generator switches to the next higher or lower scale. At the same time, an output signal is generated in the digital data output word to indicate the range in use. The circuit may be disabled during test by grounding a line on the test connector.

During ground calibration and test, the 1G suspension system in the GSE is connected to the selected axis by way of the test connector.

The points within the constrainment loop which require access during 1G tests are marked T.C. in Figure 3.3

One of the advantages of electrostatic accelerometers is the ability to change scale factor by electronic rather then mechanical means. The design combines this feature with an auto ranging circuit to cover three nominal full scale ranges of 1.5×10^{-4}, 1.5×10^{-3}, and 1.5×10^{-2}g.

The scaling change is independent in each axis. The instrument will thus always be operating on the most sensitive scale. The scale factor and switch points are shown in Table 1.

Range	Axis	± Full Scale Micro-g's	Switch Points (Increasing Input)	Switch Points (Decreasing Input)
A	X	15,000	N/A	900
B	X	1,000	1500	90
C	X	300	300	N/A
A	Y	15,000	N/A	900
B	Y	1,500	1500	90
C	Y	300	300	N/A
A	Z	15,000	N/A	900
B	Z	1,500	1500	90
C	Z	150	150	N/A

N/A - Not applicable.

The auto ranging function may be disabled during test and calibration in a 1G environment. The disable signal is introduced by way of the test connector. This prevents switching in the presence of high noise environments and allows measurement of the margin of constrainment capability beyond the switch points.

The range in use is indicated by the state of two data bits in the output data word.

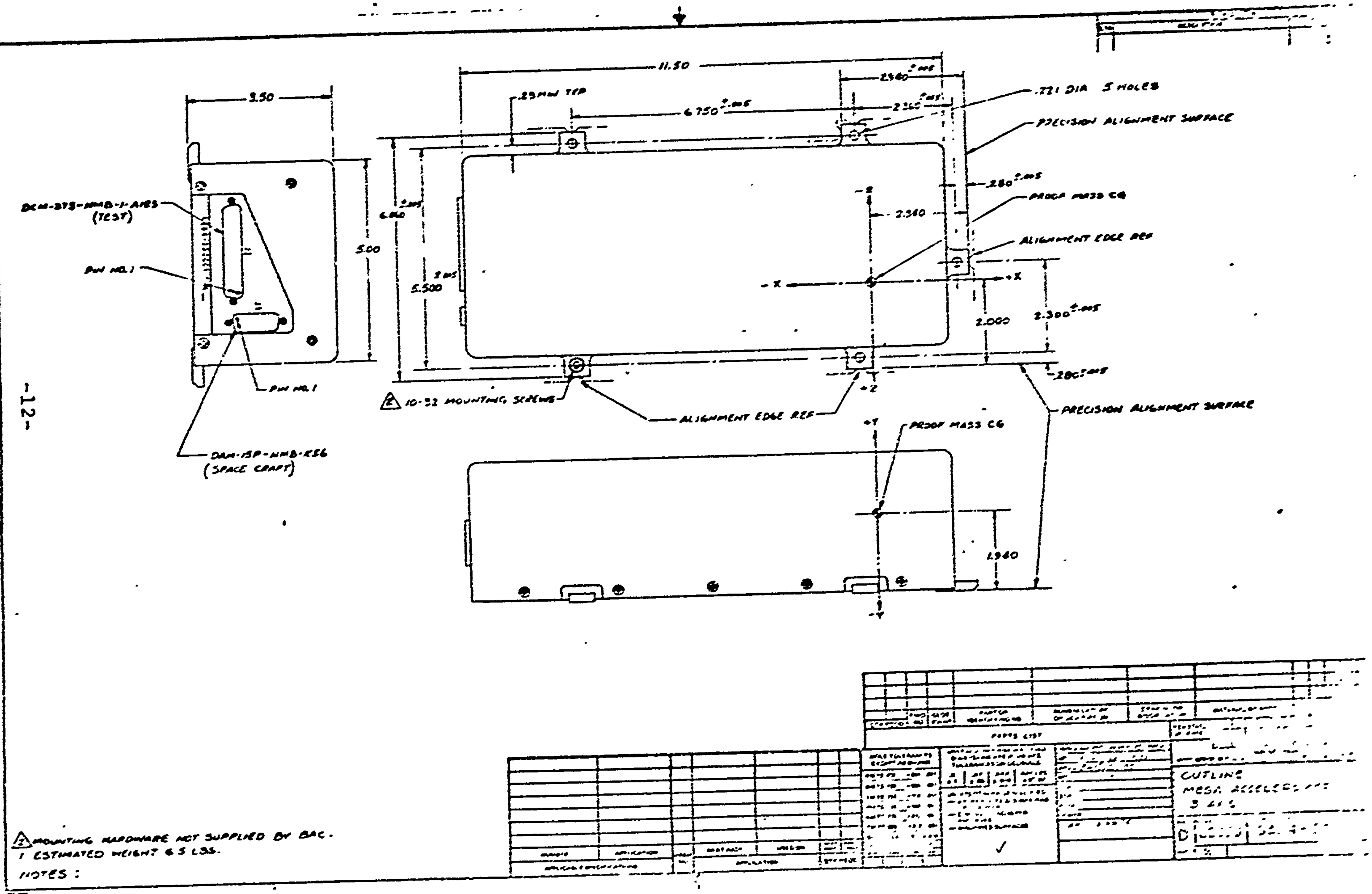
In orbital operation, system power is applied, and capture of the proof mass is automatically obtained by the auto ranging circuit.

The dc output signal of the constrainment loop, which is proportional to input acceleration, is converted to a pulse rate. Each pulse represents an increment of velocity. The pulses are accumulated in an up-down (bi-directional) counter for a predetermined period of time. The output data word thus represents the average acceleration over this "sample time" period. The digital output signal is described in detail in the electrical interface design section.

4. INTERFACE DESIGN TO HOST VEHICLE

A. Mechanical

The 3-axis MESA is packaged in a single unit as described by Bell drawing number 6384-300001. The location of mounting holes, proof mass center of gravity location, connector location and maximum outline dimensions are defined by this drawing.


11.50
2.50
2.940 ±.005
2.360 ±.005
6.750 ±.005
.25 MIN TYP
.221 DIA 5 HOLES
PRECISION ALIGNMENT SURFACE
.280 ±.005
PROOF MASS CG
2.340
ALIGNMENT EDGE REF
DCM-37S-NMB-1-A183 (TEST)
PIN NO.1
5.00
6.060 ±.005
5.500 ±.005
2.000
2.300 ±.005
.280 ±.005
10-32 MOUNTING SCREWS
ALIGNMENT EDGE REF
PRECISION ALIGNMENT SURFACE
DAM-15P-NMB-K56 (SPACE CRAFT)
PROOF MASS CG
1.940
PARTS LIST
OUTLINE
MESA ACCELEROMETER
MOUNTING HARDWARE NOT SUPPLIED BY BAC.
1 ESTIMATED WEIGHT 6.5 LBS.
NOTES :

The base and cover are aluminum and basic finish is clear alodine. The cover was painted black to provide the required emissivity for thermal control.

The bottom surface of the four mounting feet form an alignment reference plane which in combination with two reference edges define the location of the three axes.

Alignment of the accelerometers three axes with respect to these edges and plane are measured and recorded in the acceptance test data accompanying each unit.

Alignment in the satellite was accomplished by the use of alignment edges as shown on the drawing. This allows the unit to be installed with the five mounting bolts loosely fastened. The unit is then held firmly against the edges and surface and the mounting bolts tightened to the required torque

This method allows measurement of the alignment of the edges to the satellite reference axes by means of a fixture prior to installation of the flight unit.

B. Thermal

Thermal interface is dependent on the internal power dissipation of the accelerometer and the radiation and conduction paths provided by the satellite. The maximum power dissipated is 11.7 watts. The six surfaces of the container provide a total of 230 square inches for radiation. The emissivity of these surfaces was controlled by application of different paint patterns.

The conduction path is provided by the four mounting feet which are in direct contact with the satellite structure. The total contact area is 2.5 square inches. A small amount of conduction is also provided by the cable harness.

A thermal analysis conducted by the spacecraft contractor shows a nominal 75°F with a ±15°F change during the orbit period.

C. Electrical

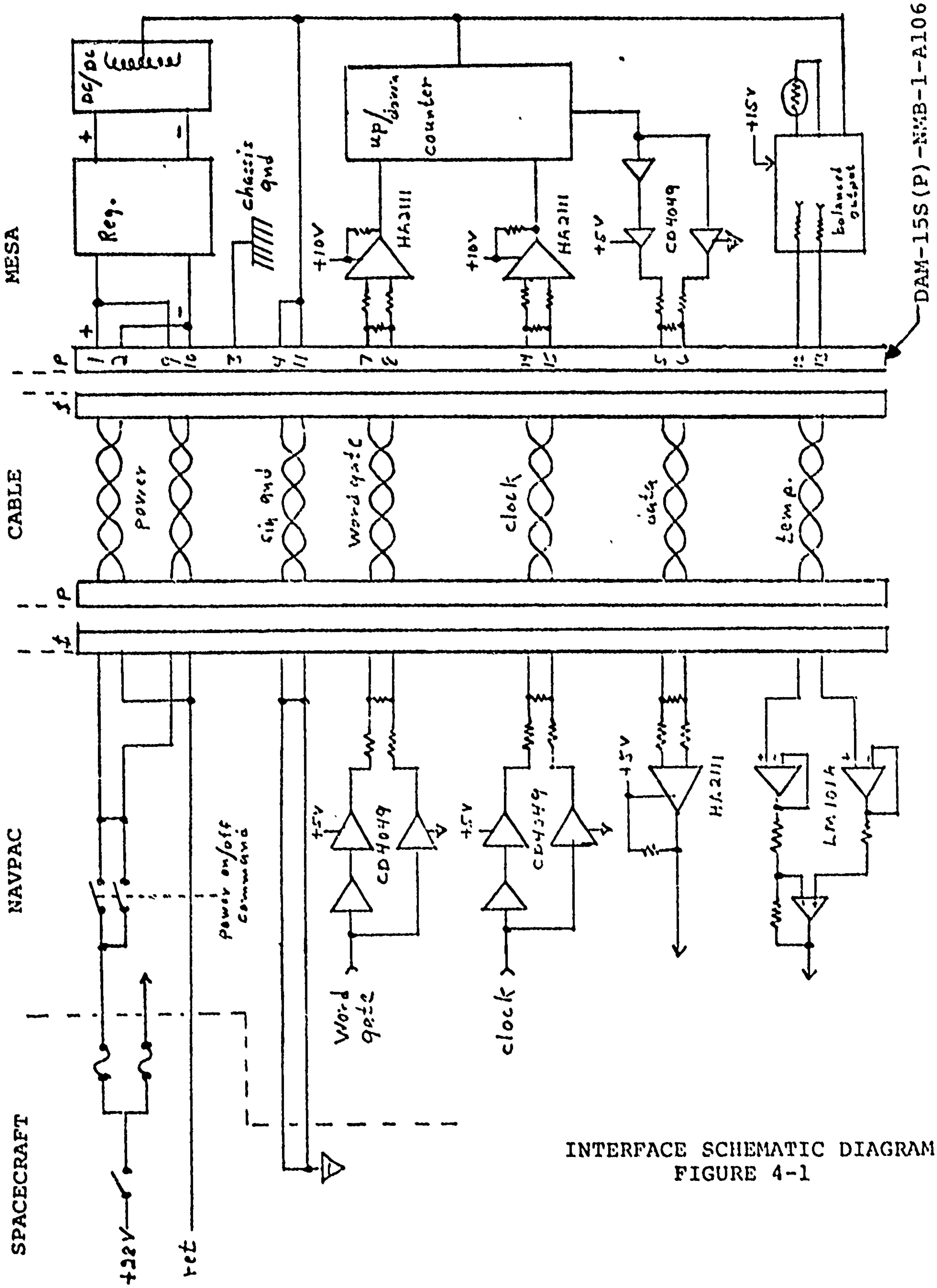
Electrical interface is provided by a single 15 pin connector which is physically located and described on Bell drawing 6384-300001.

The interface schematic diagram, Figure 4-1, shows each of the pin functions provided. Time phasing of the digital signals is shown in Figure 4-2.

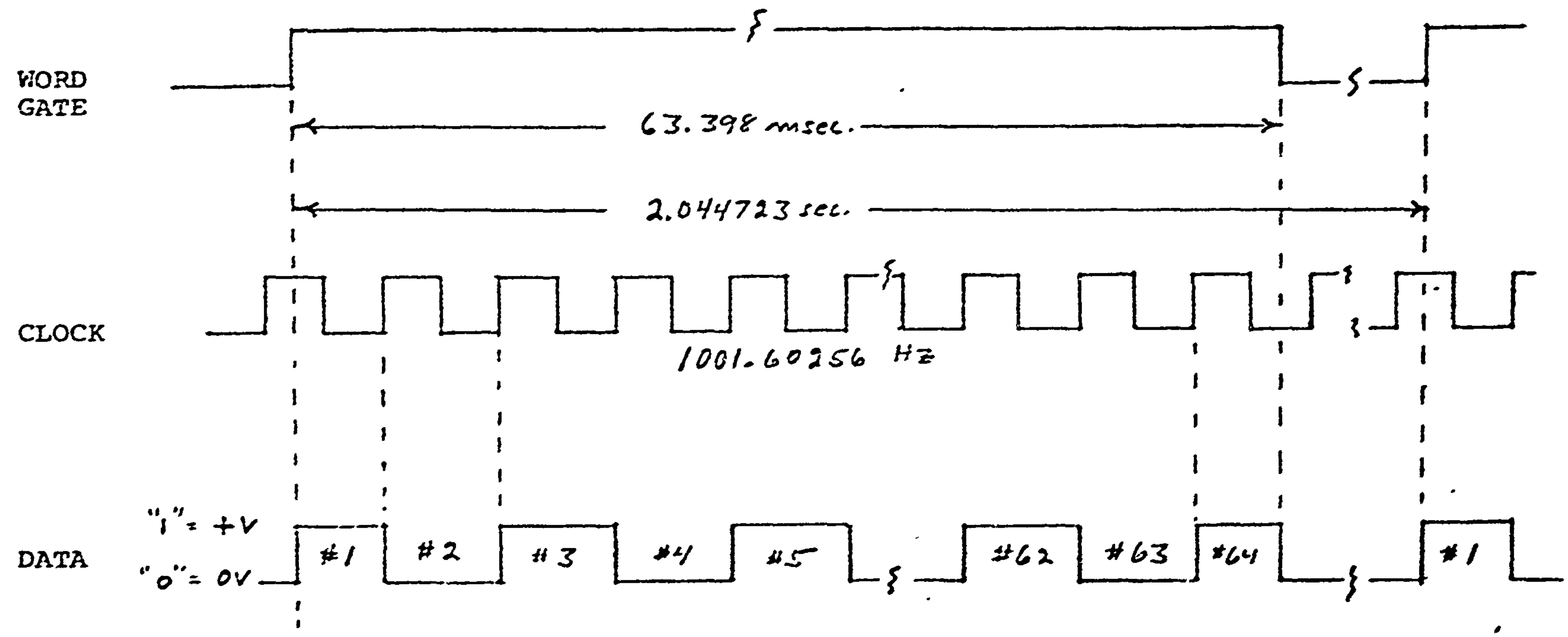
Power

Power is provided by means of redundant twisted pair of #20 wire. The plus side is controlled by command via a double pole single throw relay in the host vehicle. The relay has a minimum contact ratings of 2 amps steady state and 5 amps peak. Line voltage is 28 ±4 volts d-c and nominal current drawn in flight is 400 milliamperes. The 28 ±4 volts is regulated within the MESA to ±1% prior to conversion to the secondary voltages.

The signal ground is the secondary center tap of the dc to dc converter output transformer and is thus electrically isolated from the power input lines. Signal ground appears on



INTERFACE SCHEMATIC DIAGRAM
FIGURE 4-1



DIGITAL SIGNAL TIME PHASING
FIGURE 4-2

two connector pins and is carried to the Geopac by a twisted wire pair. A single pin is connected to the MESA enclosure and allows connection of an external chassis ground if desired.

Digital Signals

The word gate and clock signals are generated in the NAVPAC and appear as differential outputs on twisted wire pairs. The output drivers are CMOS CD4049A's operating from +5 VDC. The receivers in the MESA are HA2111's operating from +10 VDC.

The word gate has a duration of 63.398 msec and occurs at periods of 2.044723 seconds. The clock signal is a nominal 50% duty cycle and is generated at a frequency of 1001.60256 Hz.

The data output of the MESA consists of a single 64 bit word which contains acceleration, polarity, and range information of all three axes.

Bits #1 and #64 are 75% of a clock period with all other bits equal to one clock period.

Bit sampling in the NAVPAC occurs at the negative going transition of the clock signal.

Data assignment within the 64 bit word is as follows:

Data	Bit Number
X Axis Acceleration	1 to 15
X Axis Polarity	16
X Axis Range	17 and 18
Y Axis Acceleration	19 to 33
Y Axis Polarity	34
Y Axis Range	35 and 36

Data	Bit Number
Z Axis Acceleration	37 to 51
Z Axis Polarity	52
Z Axis Range	53 and 54
Not used	55 to 64.

The data output line is driven differentially by a CD4049A and the NAVPAC receiver is an HA2111. A single twisted pair is used for this line in the cable.

Analog Signals

A single analog output signal is generated within the MESA to indicate temperature of the instrument. The signal appears on a balanced output line and is received in the Geopac by a pair of LM101A amplifiers. The signal is normally in the range of 0 to +5 volts dc.

5. GROUND SUPPORT EQUIPMENT

The Ground Support Equipment (GSE) is designed to simulate the satellite electrical systems, and provide a means for bench or operational checks without the need for any special test equipment.

The GSE consists of three items, a test set, interconnecting cable, and tilt fixture. The test set provides power and signal input/output control. The interconnecting cable carries all the electrical connections to the accelerometer and simulates the satellite wiring harness. The tilt fixture provides a means for holding the accelerometer in a stable attitude and permits the input acceleration to each axis to be controlled individually.

Minimum extra equipment required are several external dc power supplies.

Test Set - This unit consists of a metal case with movable cover to protect the front panel controls and meters. The panel may be removed for servicing.

The unit will provide the following functions:

1. Control input power application.

2. Monitor input line current and voltage by means of self contained meters.

3. Provide a 1g forcing generator with the capability of connecting it to either one of two of the three axes for ground test and calibration.

4. Provide a panel meter to display the dc constrainment loop output signals of all three axes.

5. Provide a clock and sample time signal to simulate the satellite sync signals.

6. Provide test points to display or record the digital output words and internally generated clock and sample time signals.

7. Provide a means to disable the automatic range switching function during calibration.

Interconnecting Cable - This cable simulates the satellite wiring harness and provides all connections between the test set and the accelerometer during bench and calibration tests.

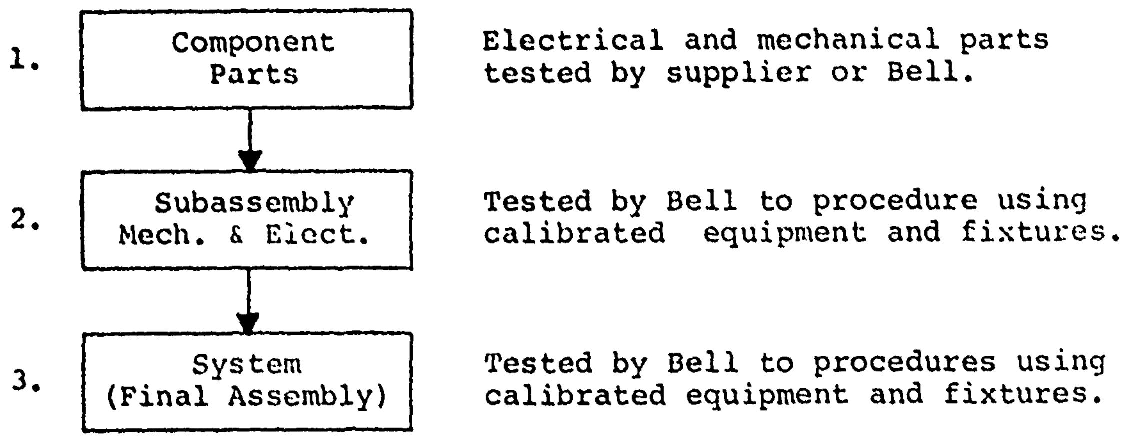
Tilt Fixture - The tilt fixture provides a means for holding the accelerometer in a stable attitude on any reasonable flat surface. It consists basically of two flat square plates joined on one end in the form of an "L" shaped assembly. A three point surface contact is provided in two planes. Each has a micrometer type adjustment screw to tilt the axis through small angles about horizontal. It may also be used as a course check of scale factor for full scale ranges in the order of 10^{-2}g. It permits functional test of each axis for both + and - input accelerations.

6. TEST PROGRAM

The test program for the 3-Axes MESA was designed to prove a high degree of reliability and provide the necessary data to assess performance against predicted values.

Testing was performed at various stages of assembly and fabrication to assure that each portion of the system was ready for the next level of integration.

The major steps of the test program are shown in the diagram below. A brief description of each step follows.



Test Levels

<u>Test Level 1 (Component Parts)</u>

Component parts such as resistors, capacitors, transistors, and integrated circuits are purchased by Bell to either government established reliability (ER) specification, or "hi-rel" specifications of the individual manufacturers. Examples of the first type are MIL-R-39008 for resistors, MIL-C-23269 and MIL-C-39014 for capacitors, and MIL-S-19500 for transistors. Examples of manufacturers "hi-rel" specifications are Fairchild Unique 38510, Texas Instruments Mach IV program, and Harris Dash 8.

The procurement of tested parts is the most economical method of assuring a high degree of reliability in the finished circuit. Subsequent levels of testing are designed to detect any faulty parts which would have passed through this screening or suffered damage at installation.

Upon receipt, the parts are subjected to receiving inspection which verifies that the part is identified per the purchase order and that all certifications and test data accompany the part as specified on the purchase order.

The parts are then stored in bulk form in secure areas until ready for assembly into the individual circuit boards.

Test Level 2 (Subassembly)

The individual circuit board is tested in two steps. The initial test is performed after assembly of all parts on the board.

After initial test, the board is inspected for soldering and workmanship. It is then coated and final tested. A final inspection of the completed board is now performed. After this the circuit is ready for installation and test at the system level.

A test procedure and data sheet is written and followed for each circuit. The data sheet defines acceptable limits for each parameter measured or indicates a "reference only" type of reading. The test fixtures and test equipment are described in the procedure. In all cases, the equipment used is certified to be within calibration and the test fixtures have been inspected and calibrated if required.

Test Level 3 (System)

Testing at the system level covers standard electrical tests and environmental tests. The test sequence and a brief description of each test is shown below:

System Test Sequence

*SET
Vibration and Pyro Shock
SET

*SET = Standard Electrical Test

Standard Electrical Test

This test is a set of readings taken to verify that performance of major characteristics are within specified limits. These include the following as a minimum: power, scale factor, null bias, range changing, and output data at prescribed input acceleration levels. The tests are performed at ambient temperature and pressure. A detailed procedure and data sheet was written to describe the tests and record the data for each piece of flight hardware.

Vibration and Pyro Shock

Vibration and pyro shock tests were accomplished to verify the mechanical integrity of the design. The level of vibration and shock were adjusted to the particular requirement of this satellite's environmental specification.

The random vibration levels which the unit passed successfully are listed below:

Overall (g RMS)	Frequency Range (Hz)	Spectral Density (g^2/Hz)
8.0	20 to 100	Increasing at 6 dB/octave
	100 to 1000	Flat at 0.1 g^2/Hz
	1000 to 2000	Decreasing at 6 dB/octave

The pyro shock tests which the system successfully passed in all three axes, are shown in Figure 6-1.

As indicated in the test sequence, a standard electrical test was performed before and after vibration to determine the effects of the test. In addition, the cover was removed and the unit was inspected for evidence of any physical damage.

7. CALIBRATION

Calibration tests were performed at five temperatures to obtain the temperature coefficient of the scale factor over the anticipated temperature range in orbit.

At each temperature, the output data (analog and digital), and the temperature monitor d-c voltage were recorded.

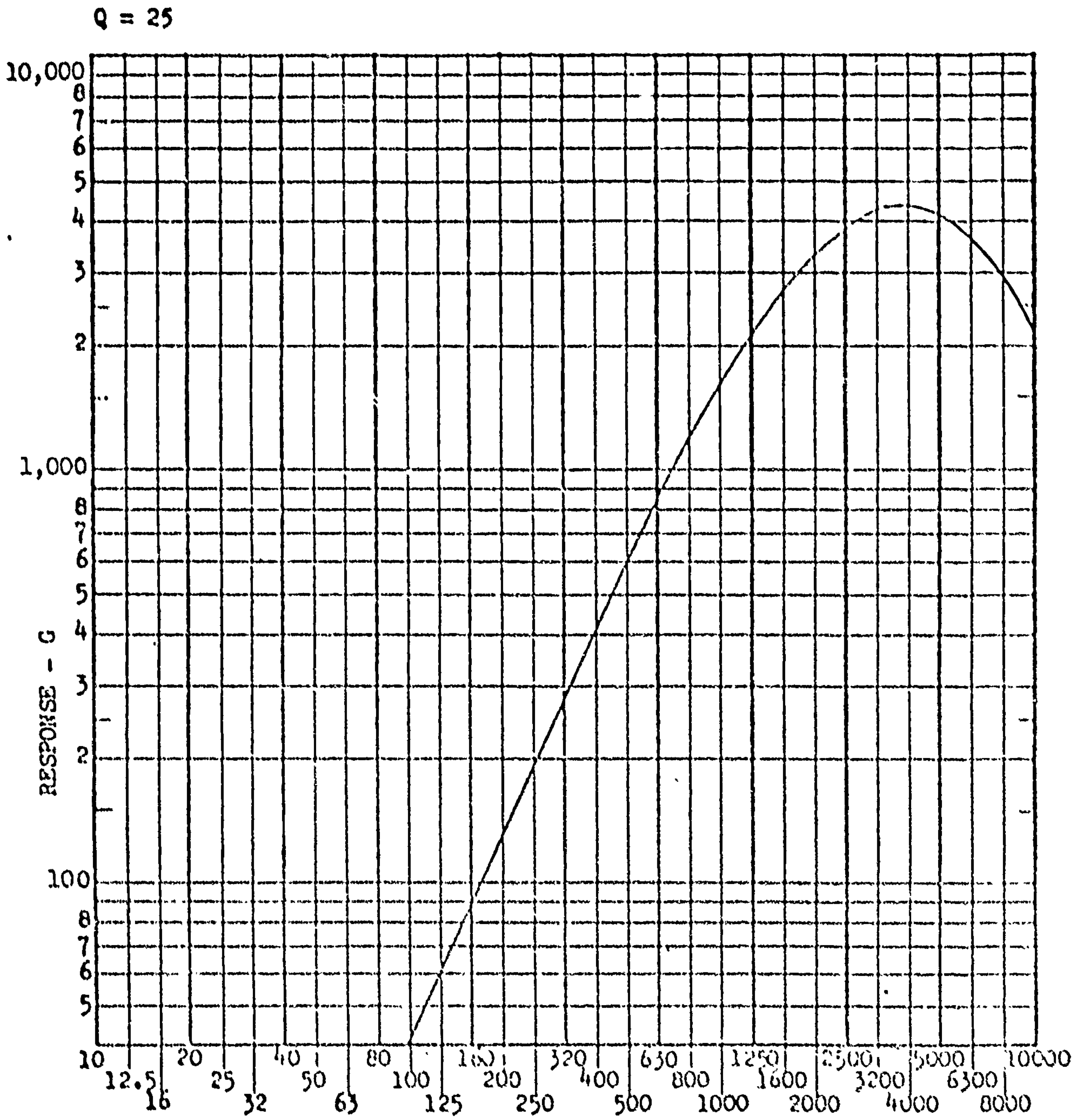
Two calibration cycles were completed on each instrument. The temperatures and test parameters used are shown on Table 7-1.

Upon completion of the calibration tests, a standard electrical test was again performed. This was the final test prior to delivery of the system.

All test data sheets were reproduced and included as part of the acceptance test data package.

8. SPACECRAFT INTEGRATION

Integration of the 3 Axis MESA with the flight vehicle was carried out in two stages. An initial electrical and signal compatibility test was conducted with the NAVPAC hardware at the Applied Physics Laboratory of Johns Hopkins University (APL).



PYRO SHOCK ENVIRONMENT AT MESA

FIGURE 6-1

TABLE 7-1

CALIBRATION SCHEDULE FOR NAVPAC MESA

Temperature (°F)	1st Calibration X	1st Calibration Y	1st Calibration Z	2nd Calibration X	2nd Calibration Y	2nd Calibration Z
60			L			CL
75	CL	CL	L			L
90	L	L	L	CL	CL	L
105	CL	CL	L			L
120			L			CL

L - Linearity test, 4 points (plus) and 4 points (minus) for each range A, B and C. Each point takes average of two readings on A range, four readings on B range, and six readings on C range. Both digital and analog data taken at each point.

CL - Linearity test on C range only with six readings per point, 4 points plus, and 4 points minus. Both digital and analog data taken at each point.

The two systems were connected using the actual interconnecting cable which was later to be installed in the first flight vehicle. The accelerometer output was set at several typical input levels in each axis and output data recorded. Tolerance levels were changed and an adequate safety factor demonstrated.

The second phase took place after delivery of the first system to the spacecraft contractor facility.

Initially the mechanical interface was checked. Alignment techniques were demonstrated and no major difficulties were encountered.

Following mechanical interface tests, the unit was connected to the NAVPAC pallet via the interconnecting cable and a series of electrical checks made to demonstrate the integrity of all cables and connectors.

These tests were followed by acoustic and thermal vacuum tests. After each environmental test, the unit was delivered to the Bell representative and a bench functional test, with the proof mass constrained at 1G, was performed. The units successfully passed these tests and were subsequently installed in the host vehicle in preparation for flight.

9. FLIGHT PERFORMANCE

The first 3 axis MESA System (Serial Number 1) was placed in orbit during the later portion of the contract period. The second and third systems have been delivered and are in various stages of pre-flight testing at the spacecraft contractor facility.

Flight data available to date indicates the main objectives of the instrument development program were achieved.

The major objective was to develop an instrument that would measure acceleration in three axes with the use of a single proof mass. Data shows response to inputs in all three axes.

One secondary objective was to remove the 1G constrainment capability from the flight hardware by having the ground support equipment (GSE) perform this function. This achieved volume, weight, power and cost reduction since this capability is not required in orbit.

Flight test data show that capture of the proof mass in all three axes was achieved within the allocated time of 60 seconds or less, without the 1G capture capability.

Another secondary objective was the incorporation of automatic range scaling to eliminate the need for ground commands. This results in having all three axes operate on the most sensitive scale at all times.

Flight data show that this approach to range scaling was valid. All three axes were automatically switched to their lowest scale within a few seconds after the initial "turn-on capture sequence" was completed.